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# An IoT Scheduling and Interference Mitigation Scheme in TSCH using Latin Rectangles

Chérifa Boucetta*, Boubakr Nour§, Hassine Moungla*‡, and Laaziz Lahlou¶
*Université de Paris, LIPADE, F-75006 Paris, France
‡UMR 5157 CNRS, Telecom SudParis, Institut Polytechnique de Paris, Palaiseau 91120, France
§School of Computer Science, Beijing Institute of Technology, Beijing, China
¶École de Technologie Supérieure, University of Quebec, Montreal, Canada
Email: {cherifa.boucetta, hassine.moungla}@parisdescartes.fr, n.boubakr@bit.edu.cn, laaziz.lahlou.1@etsmtl.net

***Abstract*—Time Slotted Channel Hopping (TSCH) is one of the most used MAC mechanisms introduced by the new amendment IEEE 802.15.4e. It combines both slotted access with channel hopping technique to allow multiple communications while exploiting the 16 available channels of 2.4GHz band. The channel hopping mechanism of 802.15.4e considers an interference-free environment and does not specify how to build and manage a schedule for communication purpose. In this paper, we propose a new distributed channel hopping scheme that exploits Latin rectangles to avoid interference and collisions. In essence, the scheduling of links is performed by Latin rectangles where rows are channel offsets and columns are slot offsets. Thus, the frequency of communication is derived using Latin rectangles. Consequently, interference and multi-path fading are mitigated with more reliability and robustness. The efficiency of the proposed scheme has been validated by extensive simulation.**

## I. Introduction

The Internet of Things (IoT) [1] can be defined as the future network that interconnects physical devices, vehicles, smart buildings, sensors, and actuators aiming to build smart environments including smart cities, smart homes, smart hospitals, etc. Such complex environments comprise a huge number of heterogeneous devices from different vendors that may use different operating systems and protocols [2]. Consequently, different challenges may arise during the deployment of IoT applications including the scalability, trust relationship between networks and devices, devices' resource limitation, and the diversity of applications requirements and channel utilization [3]. Thus, there is a huge need to develop a unified stack and underlying architecture to support different kind of devices, and easily connect with the Internet infrastructure.

To date, several efforts and standardization activities have been shown by international organization and researchers to support different kind of sensors in different domains. IEEE 802.15.4 standard that includes ZigBee, Bluetooth to cite a few are very abundant in the literature and have been studied extensively. Nonetheless, none of these standards meet the requirements of IoT in terms of communication reliability and protection against interference/fading [2].

A survey on IEEE802.15.4e may be found in [4] which highlights the new standard and gives an overview of efforts that have been proposed since its release. The new amendment introduces new MAC protocols (known as MAC behavior modes), namely Time Slotted Channel Hopping (TSCH), Deterministic and Synchronous Multi-channel Extension (DSME), and Low Latency Deterministic Network (LLDN). The main purpose behind the design of TSCH is to increase the number of applications supported by IEEE 802.15.4 devices and reach channel hopping and low-power operation, and thus improve the reliability of transmission [5]. IEEE 802.15.4 is essentially proposed for industrial wireless sensor networks.

The IETF (Internet Engineering Task Force) 6TiSCH working group [6] defines mechanisms that combine the interoperability of the IP protocol with the high reliability and the low power consumption of TSCH. The integration of TSCH within the IoT architecture is ensured by the definition of the 6TiSCH operation sub-layer (6top) [7]. 6Top defines the schedule management algorithm and negotiation cells approach between nodes. Indeed, 6top includes a Scheduling Function (SF) that control the communication for cell reservation between neighboring nodes.

Although TSCH can achieve a fixed throughput and maximum latency in high traffic load [8], it still faces challenges with IoT such as the necessity to understand future traffic flows which is infeasible in real scenarios. It is important to highlight here that distributed schemes are more realistic than centralized, where nodes can work in an autonomous manner (e.g., hotspot networks). Furthermore, IEEE 802.15.4e standard details the used mechanism by TSCH MAC to execute a schedule in the network but it does not indicate how to build an optimized schedule. In this work, we are mainly interested in the TSCH MAC behavior. We propose a distributed scheduling and interference mitigation scheme using Latin rectangles that aims to define the scheduling function of TSCH cells and tacking into account channels already allocated by the neighborhood. To evaluate our solution, we present a simulation-based evaluation of our approach and a 6TiSCH scheduling algorithm. The performance of the proposed scheme is studied through extensive simulation using the 6TiSCH simulator. Results show a significant improvement, in particular, a decrease of the average of colliding cells, latency and consumed energy.

The rest of the paper is organized as follows. Section II reviews related approaches in the literature. Section III gives

an overview of our network model, and briefly recall of Latin squares. Section IV describes the proposed scheme. Section V discusses the simulation results. Section VI concludes the paper.

## II. Background & Related Work

Several MAC protocols for wireless communication have been studied and proposed extensively for more than a decade [9]. Wireless communication can be achieved by following contention methods i.e Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), or Time Division Medium Access (TDMA).

Time Slotted Channel Hopping MAC behavior mode combines time slot technique with multi-channel and channel hopping mechanisms. With time slot technique, collision among concurrent nodes is mitigated while multi-channel and channel hopping techniques allow several nodes to communicate at the same time slot using different channel offsets. Hence, the overall network throughput is increased, and a high communication reliability is achieved. On the other hand, various algorithms have been proposed for TSCH networks. For instance, Hermeto *et al.* [10] provided an overview study for TSCH algorithms targeting both distributed and centralized scheduling. A centralized approach assumes that the Path Computation Element (PCE) has a comprehensive knowledge of the network topology and traffic, while a distributed approach permits each node in the network to reserve as many cells as required to perform the communication.

Marinkovic *et al.* [11] developed an energy efficient TDMA-based MAC protocol tied for Wireless Body Area network. Authors supposed a static body posture of patients. The communication pattern was under Master-Slave architecture where sensors communicate with a gateway using a predetermined slot assignment. In their work, a simple but yet interesting computational method was derived taking into account the sampling rate of sensors like Electroencephalogram or Electrocardiography. However, the main drawback of this approach is that it is hardware dependent.

Chen *et al.* [12] proposed an intra- and inter-interference mitigation protocol for medical applications namely 2L-MAC. A channel switching technique and TDMA-polling based technique are leveraged. The protocol is built upon two layers. The first layer deals with intra-BAN communication, which is managed using a hub that coordinates the sensors. In the second layer, inter-BAN interference is mitigated using carrier sensing that avoids collisions among collocated BANs with a specific backoff mechanism that considers quality of service parameters (e.g., transmission delay and priority). Nonetheless, the authors did not show results about their protocol regarding inter-interference mitigation as claimed.

Fafoutis *et al.* [13] introduced an adaptive and static scheduling scheme to enhance the power efficiency of TSCH networks. The proposed scheme allows each pair of nodes to control their active timeslots, and activate/deactivate in a dynamic manner a subset of their allocated slots according to the traffic requirements. Hence, reduce the idle listening overhead of unused slots. Despite the distributed nature of the scheme, the work did not take the cost of blind over-provisioning into consideration.

Jin *et al.* [14] proposed a centralized adaptive multi-hop scheduling method based on TSCH MAC. The proposed method aims to provide a low latency for time-constrained applications and reduce the collision by allocating backup slots only to those nodes that are one-hop away from the sink node. The major drawback of this work is the centralized nature, as well as the possibility to not cover nodes with bad links due to the fact that it can allocate unnecessary slots.

Fahs *et al.* [15] presented a scheme that tends to overcome the allocation of identical cells problem in 6TiSCH protocol and co-locate pair of nodes. The proposed solution consists of enabling node to overhear previously exchanged cells and prevent nodes from re-use the already assigned cells in the future allocations. While Chang *et al.* [16] proposed a low latency scheduling function that aims to daisy-chains timeslots rather than use a random fashion, and thus decrease the latency.

Although the aforementioned efforts, we exploit in this work Latin rectangles to avoid interference and achieve a larger throughput. The channel offsets and slot offsets are represented by rows and columns of Latin rectangles respectively, and thus derives the frequency of communication.

## III. Network Model & Latin Squares

This section describes the used IoT network model, as well as different preliminaries about Latin Squares.

### A. Network Model

In this work, we consider a network composed of several nodes (one gateway and a set of sensors) deployed in an industrial automation environment. Nodes monitor equipment and processes, while gateway gathers sensors' data to send it out to a central processing station.

### B. Latin Squares

In the following, we present the required definitions of Latin squares [17] that we used in our proposed approach for scheduling in the channel hopping mechanism of TSCH.

**Definition 1.** A Latin square is an $N.N$ matrix filled with $N$ distinct symbols, each symbol per row and per column is unique. Below, is an instance of a Latin square filled with 5 distinct symbols ranging from 1 to 5.

$$\begin{bmatrix} 1 & 2 & 5 & 3 & 4 \\ 2 & 3 & 1 & 4 & 5 \\ 3 & 4 & 2 & 5 & 1 \\ 4 & 5 & 3 & 1 & 2 \\ 5 & 1 & 4 & 2 & 3 \end{bmatrix}$$

**Definition 2.** A matrix noted $N.K$ containing unique symbols $(x_{i,j})$ ranging from 1 to $K$ in each row and column is said to be a Latin rectangle.

In this paper, we denote by a symbol the channel to time-slot assignment for a sensor. Hence, we use Latin rectangles in order to to build an optimized schedule.

## IV. TSCH Scheduling and Interference Mitigation using Latin Rectangles

In the following, we detail the proposed scheme for TSCH scheduling and interference mitigation using Latin Rectangles.

### A. TSCH Overview

IETF draft [6] highlights the TSCH protocol. In TSCH, both communication and synchronization between nodes is defined by a schedule that divides the wireless spectrum into time and frequency over a scheduling period referred to a slotframe. Thus, TSCH schedule can be considered as a matrix where columns are frequencies and rows are time slots. The number of time slots defines the size of the slotframe which is repeated continuously over time. The basic unit of bandwidth scheduled is called *cell*. In each cell of the TSCH schedule, a node can communicate with his neighbours by sending or receiving packets.Each cell is indexed by a specific timeslot and a channeloffset. The channel offset is a virtual channel that is translated into a frequency while the slot offset sets the location of the cell in time from the beginning of the current slotframe. In a cell, each node knows when to communicate and on which channel. According to the amendment, nodes calculate the frequency to communicate on according to the following formula:

$$frequency = F([ASN + channelOffset] \pmod N)) \quad (1)$$

where *ANS* is the Absolute Slot Number. The ASN is incremented at each slot and shared by all nodes in the network. $F$ is the function of a lookup table that contains the set of available channels indexed by channel offset. The value $N$ defines the size of this table, i.e. the available frequencies. Basically, if two nodes want to communicate, they need to translate the channel offset into real frequency using the above function.

In TSCH, the same schedule repeats throughout the slot-frames instead of performing frequency switching within each slot-frame in case of interference or unstable channel, where a random scheduling approach is used. However, this might decrease the network performances and do not meet the targeted trade-off between energy consumption, robustness, and latency.

### B. SIM: Scheduling and Interference Mitigation Scheme

A schedule is composed of several cells where each cell is characterized by a slot offset and channel offset, and reserved for a specific node to perform an action (transmit or receive). The amendment does not specify how to build such schedule and supposes an interference-free environment.

Hence, our proposed scheme is motivated by the fact of combining a theoretical framework, i.e. *Latin rectangles* with specific characteristics of sensors (e.g., communication data rate) to come up with a solution that links up both aspects in one core. Furthermore, the process of building a schedule relies on the formula that translates channel-offset on to real frequencies.

*1) Slot Assignment:* In our approach, the slot assignment is done based on the distribution of sensors within the Latin rectangle. Therefore, the assignment of slots is not static, and sensors get their slots according to *Definition 1*.

In addition, several slot assignment may be applied given the size of the Latin rectangle. Yet, we follow the philosophy behind the design of TSCH which is the customization. Thus, our approach fits into that principle.

*2) TSCH Frame Computation:* The size of the Latin rectangle is defined by the number of channels and the number of time slots. We exploit the 16 channels of the 802.15.4e standard within the 2.4GHz band. Regarding the number of time slots, our work is mainly motivated by the computational method designed in [11]. Similar to their work, we compute the number of time slots within the slot-frame respecting TSCH slot frame structure according to sensor sampling rate f$s$ (bit/s) and the communication data rate f$c$ (bit/s).

Figure 1 illustrates an example of a given TSCH slot-frame structure in 802.15.4e amendment.

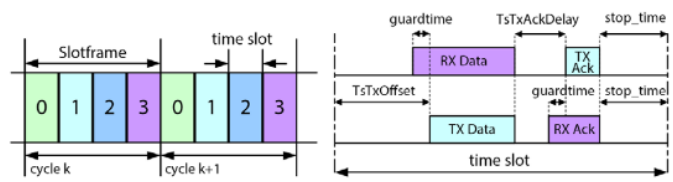



Fig. 1: TSCH Slotframe (left) and Timeslot (right)

The number of time-slots is computed as follows:

$$N_{slots} = \frac{TSCH_{slotframe}}{TSCH_{slot}} \quad (2)$$

where $TSCH_{slotframe}$ and $TSCH_{slot}$ (or timeslot) are presented in Figure 1. These parameters are calculated by the following formulas.

$$TSCH_{slot} = \alpha + \beta + \gamma + \delta \quad (3)$$

$$\beta = \frac{N_{data}}{fc} = fs \times \frac{TSCH_{slotframe}}{fc} \quad (4)$$

$$\gamma = \frac{Nack}{fc} \quad (5)$$

and the number of TSCH slots is defined as:

$$N_{slots} = \frac{fc \times TSCH_{slotframe}}{fs \times TSCH_{slotframe} + Nack + fc \times (\alpha + \gamma)} \quad (6)$$

where $\alpha$ denotes TsTxOffset, $\beta$ TxData, $\gamma$ TsTxAckDelay, $\delta$ TxAck, $N_{data}$ sampled bits during one TSCHslotFrame, and $Nack$ is the ACK/NACK message bits.

*3) SIM Algorithm:* The proposed SIM scheme, as summarized in Algorithm 1, starts by computing the number of slots required by the sensor nodes provided with their characteristics in terms of communication data rate and sampling rate with respect to the TSCH slot-frame. Then, the schedule is defined based on the Latin Rectangle property where a unique channel and a unique time-slot are allocated to each communication. Hence, the Latin rectangle's property ensures that a node $n_i$ has a different channel allocation pattern compared to his neighbors within a timeslot which avoids inter-nodes interference and collisions.

**Algorithm 1:** SIM Algorithm

```
▹ Initialization
Nodes ← set of nodes;
Channels ← set of available channels;
N_ch ← total number of channels;
▹ Slots computation
Compute the number of slots according to Eq. 6;
TS ← set of available slots;
for (t_s ∈ TS) do
    if (Channels ≠ ∅) then
        Setup a Latin rectangle;
        Build the communication schedule;
    else
        schedule gets random(1,N_ch) ;
    end
end
```

A cell is assigned to the link $(k,l)$ when a node $n_k$ sends a packet to his neighbour $n_l$. At the beginning of each frame, all links are examined sequentially and each node calculates the set of available channels. Then, it builds the Latin rectangle and assigns channels to time-slots considering his traffic data. If the number of needed cells is bigger than the available channels, the set will be empty, then the node assigns channels randomly as mentioned in the TSCH. Basically, this strategy allows a dynamic management of interference and collisions without affecting other nodes. The energy consumed by a node is calculated using the model [18].

## V. Performance Evaluation

In order to validate and evaluate the performance of the proposed SIM scheme, different simulation experiments have been conducted by using 6TiSCH simulator. It is an implementation of IEEE802.15.4e [6] that includes RPL (Routing Protocol for Low-Power and Lossy Networks) for routing and 6top [7] for the management of TSCH schedules. The RPL protocol organizes the network as a tree (DAG or directed acyclic graph) where all generated data is sent to the DAGroot (the gateway node, or sink).

### A. Simulation Parameters

We consider a $1000m \times 1000m$ area with two different densities (20 and 100 sensor nodes). The positions of the nodes are randomly arranged around the DAGroot which is located at the center of the deployment area. The packet generation rate is 1 packet/sec and 16 IEEE 802.15.4 channels are used. Each run consists of 1000 cycles, the cycle referring to one slot-frame. The minimum RSSI (Received Signal Strength Indication) value that is equal to $-97$ $dBm$ wich allows a packet reception. The timeslot duration is $10ms$, and a slotframe presents 101 timeslots. Table I summarizes experimental parameters used.

TABLE I: Simulation parameters.

| *Parameter* | *Value* |
|---|---|
| Number of nodes | 20 and 100 |
| Number of cycle per run | 1000 |
| Number of channels | 16 |
| Number of runs per simulation | 100 |
| Slotframe length | 101 |
| Timeslot duration | 10 ms |
| Area size | $1km \times 1km$ |
| Radio sensitivity | -97 dBm |

We have compared our proposed scheme to 6top defined in 6TiSCH simulator. We considered two case of study: low density with 20 sensor nodes and high density with 100 sensor nodes. We first measured the number of collided Tx cells and the number of schedule colluding Tx cells. Second, we compared end-to-end latency for SIM and 6TiSCH after scheduling was completed. Finally, we measured the energy consumption.

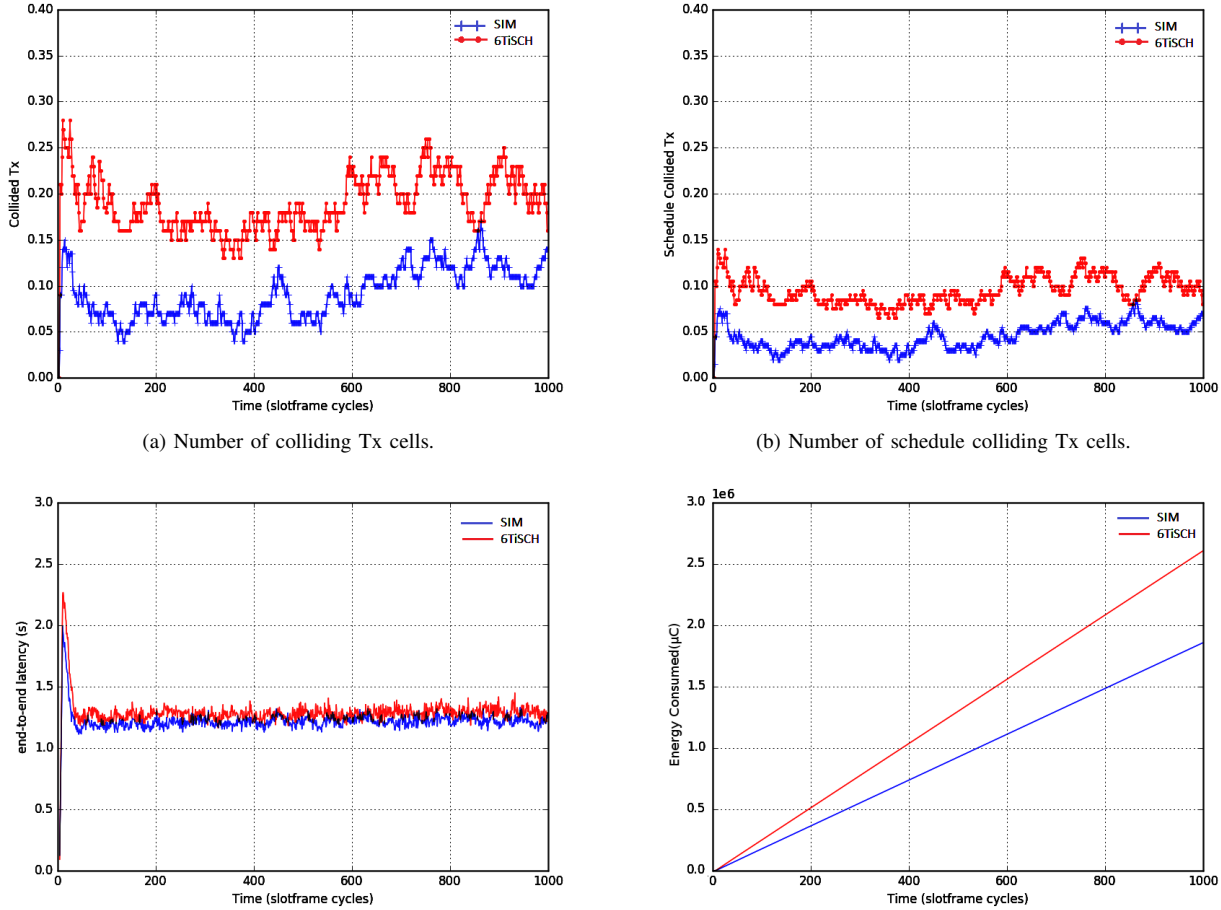
### B. Simulation Results

The simulation tests were run on the same topologies and the results present the average values with a 95% confidence interval.

A *colliding cell* is a cell that is used by many communications simultaneously and then creating the potential chance to cause collisions. As can be clearly seen in Figures 2a and 3a, SIM has a lower number of colliding Tx cells than 6TiSCH because of the Latin rectangle property in the assignment of channels to timeslots. It is clear that the number of colliding cells is varying as a function of the network density. Indeed, this number is more important in the higher density networks than lower density. This is due to the fact that the traffic generated by nodes is greater than the available number of channels dedicated to communications.

Furthermore, we notice that the number of colliding cells is increased and then stabilized when all needed cells are scheduled especially for high density. In essence, at the beginning of the simulation, all nodes exchange 6top messages in shared cells which increase the number of collisions. Then, the number of dropped packets decreased progressively when the bootstrap network phase finished, and most of needed cells for packet transmissions are allocated. Consequently, the scheduling operation is enabled to define a sufficient number of allocated cells within a timeslot considering the collision effects and negotiation errors.

Figures 2b and 3b show the variation of the number of schedule collided Tx cells over the time in both low and




(a) Number of colliding Tx cells.

(b) Number of schedule colliding Tx cells.

(c) Average end-to-end latency.

(d) Energy consumption.

Fig. 2: Low-density performance (20 nodes).

high-density networks. SIM reduces the number of schedule colliding cells which depends on the amount of data traffic. The denser the network, the more traffic is, and hence the more cells are required. The reason here is that the schedule assigns each communication to a unique channel and a unique time-slot which reduces collisions.

The average end-to-end latency for various values of the simulation parameters is presented in Figures 2c and 3c. It is the difference between the moment of the packet generation at the node and its reception by the DAGroot. The results show that the latency increases at the beginning of simulation of the network life and then stabilizes. These results show that SIM provides lower end-to-end latency and consumes less energy than 6TiSCH.

Figures 2d and 3d illustrate the way that the energy consumption varies regarding the time in a 20-nodes and 100-nodes networks respectively. In general, when the number of nodes increases, the battery life-time decreases and nodes consume more energy. This is because the higher the number of nodes, the higher the number of packet transmissions is. It is clear that SIM consumes significantly less energy compared to 6TiSCH. This is because of its significant reduction of the schedule colliding cells.

## VI. Conclusion

This paper presented an IoT scheduling and interference mitigation scheme in Time Slotted Channel Hopping using Latin rectangles, which prevents the schedule of nodes from channels that are already allocated. In this way, the proposed distributed scheme adapts the schedule to the network conditions in 6TiSCH networks and provides efficient resource allocation. The obtained results show significant improvements in latency, colliding cells, and energy consumption as well. The next phase of our research will be the deployment of the proposed scheme in a real large-scale industrial IoT testbed.

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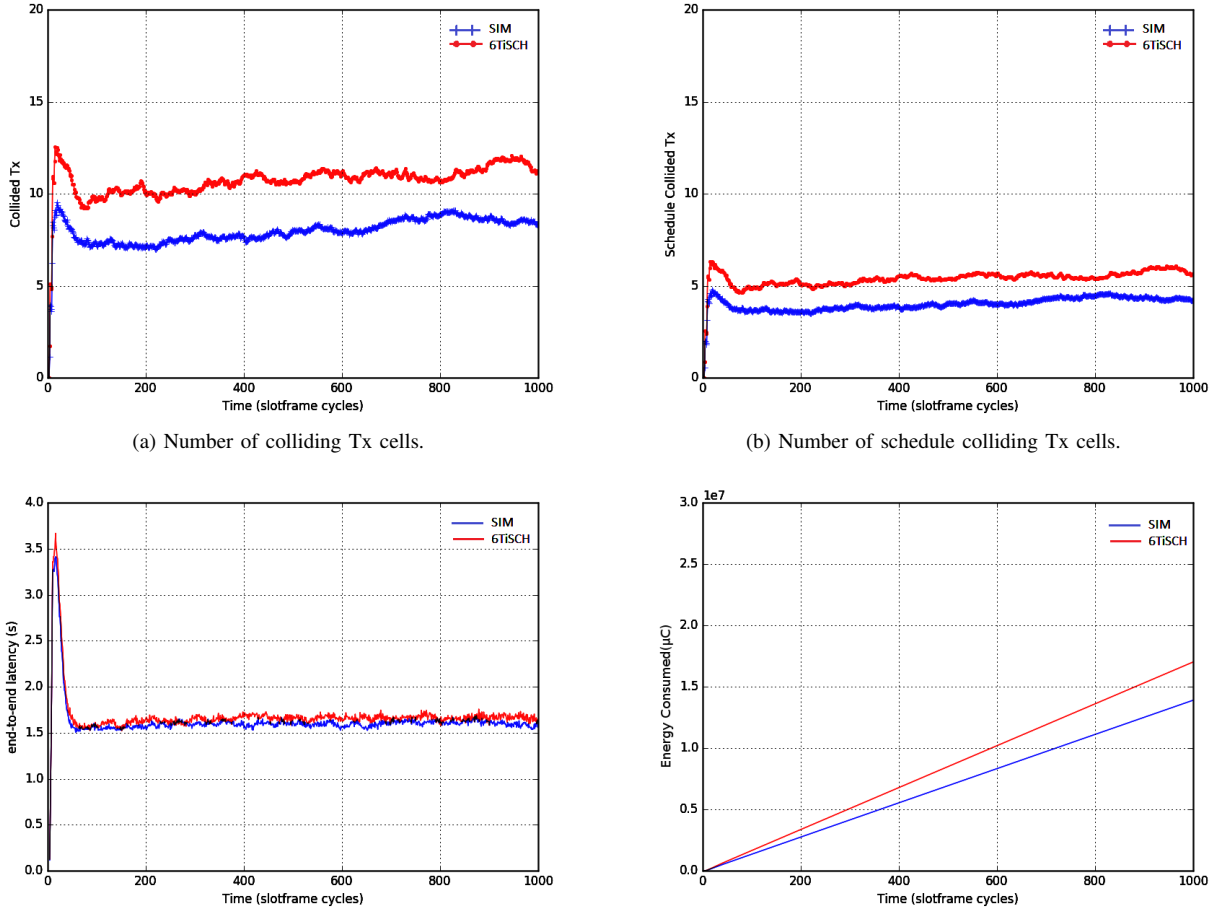


(a) Number of colliding Tx cells.

(b) Number of schedule colliding Tx cells.

(c) Average end-to-end latency.

(d) Energy consumption.

Fig. 3: High-density performance (100 nodes).


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